

## Ultra-High Energy Astrophysical Neutrino Detection, and the Search for Lorentz-Invariance Violations

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A growing class of ultra-high energy neutrino observatories based on the Askaryan effect and Antarctic ice is able to search for Lorentz-invariance violation. The ARA, ARIANNA, ANITA, and EVA collaborations have the power to constrain the Standard-Model Extension by measuring the flux and energy distribution of neutrinos created through the GZK process. The future expansion of ARA, at the South Pole, pushes the discovery potential further.

### 1. The GZK Process and EeV neutrinos at the Earth

Ultra-high energy neutrino (UHE- $\nu$ ) observations are a long-desired achievement in astroparticle physics. Clues about cosmic ray origins and potential electroweak interaction measurements from  $10^{16}$ - $10^{19}$  eV are contained within this flux.<sup>1</sup> PeV-scale neutrino observations in IceCube<sup>2,3</sup> have made possible learning about UHE- $\nu$  physics from beyond the solar system. A UHE- $\nu$  could be produced via the GZK process, given the UHE- $p^+$  spectral cutoff at  $10^{19.5}$  eV.<sup>4</sup> The next generation of UHE- $\nu$  detectors is designed around the Askaryan effect, which produces radiated radiofrequency power.<sup>5-8</sup> Antarctic ice provides a convenient medium for Askaryan radiation.<sup>9</sup> The RICE collaboration<sup>12</sup> began the field, and efforts such as ANITA, ARA, ARIANNA, and proposed EVA<sup>13,14,16,17</sup> have made progress in developing sensitivity to UHE- $\nu$  fluxes.

There is a connection between Lorentz-invariance violation (LIV) and UHE- $\nu$ , through flux limits, via the Standard-Model Extension (SME).<sup>18</sup> The SME includes LIV terms of varying dimension, proportional to small coefficients. LIV in the neutrino sector could modify the UHE- $\nu$  spectrum at Earth by introducing vacuum energy loss.<sup>19</sup> The UHE- $\nu$  detectors can place constraints on SME coefficients.

## 2. Experimental detection efforts

The Antarctic Impulse Transient Antenna (ANITA) is a balloon-borne detector with radiofrequency (RF) antennas as payload.<sup>13</sup> ANITA-1 flew in 2007-2008 with 32 separate RF channels, modified in subsequent seasons (40 channels for ANITA-2 and 48 for ANITA-3). ANITA detects man-made noise, thermal noise, and RF pulses from UHE- $p^+$ .<sup>20</sup> ANITA has a UHE- $\nu$  threshold  $E_{th} \simeq 10$  EeV, limited by RF propagation to the payload ( $\simeq 35$  km). The balloon altitude allows the detector to observe instantaneously  $V_{eff}\Omega \approx 100$  km<sup>3</sup> str of ice at 10 EeV (the effective volume times the viewable solid angle)<sup>13</sup>.

The Askaryan Radio Array (ARA) is an *in situ* array of RF detectors at the South Pole.<sup>14</sup> Three detectors are deployed, using AC power from the Amundsen-Scott base. *In situ* detectors lower  $E_{th}$  by being  $\simeq 1$  km from typical events. For example, ARA is projected to have  $V_{eff}\Omega \approx 1000$  km<sup>3</sup> str at 10 EeV, and 100 km<sup>3</sup> str at 0.1 EeV<sup>14,15</sup>. With an analysis using 2 of 37 planned stations, ARA is already competitive with ANITA below  $E_\nu \simeq 10$  EeV and with the IceCube high-energy analysis above  $E_\nu \simeq 100$  EeV. ARA is projected to detect  $\simeq 100$  GZK neutrinos in 3 years.<sup>1,14</sup>

The Antarctic Ross Ice Shelf Antenna Neutrino Array (ARIANNA) is another *in situ* detector, located on the Ross Ice Shelf.<sup>16</sup> The Hexagonal Radio Array (HRA) is the seven-station prototype. The ocean/ice boundary provides a mirror for RF signal collection, boosting effective volume through increased visible solid angle.<sup>9</sup> Extensive air showers have been observed<sup>10</sup>, and final UHE- $\nu$  sensitivity is projected to be equal to ARA. The final array design requires a  $31 \times 31$  station array, with stations separated by 1 km, from in-ice attenuation length measurements.<sup>11</sup>

The ExaVolt Antenna (EVA) is a proposed balloon-borne detector with a boosted RF effective area.<sup>17</sup> The balloon itself is the antenna, and technological improvements in balloon design are expected to boost flight durations. The EVA project is currently in the proposal stage.

## 3. LIV tests in the Askaryan-based neutrino experiments

The SME allows for UHE- $\nu$  energy loss while propagating in a vacuum.<sup>19</sup> One example is the vacuum Cherenkov effect:  $\nu \rightarrow \nu e^+ e^-$ . UHE- $\nu$  with relatively higher energies disappear, and an abundance of lower-energy UHE- $\nu$  appears. The energy loss may be treated like a decay with half life  $\tau_\nu$  given by

$$\frac{\tau_\nu}{s} = \tau_{CG} \left( \frac{E_\nu}{\text{GeV}} \right)^{-5} \frac{1}{\alpha_\nu^3}, \quad (1)$$

with  $\tau_{CG} = 6.5 \times 10^{-11} \text{s}$ , and  $\alpha_\nu$  being the constrained SME parameter.

Attributing the nonobservation of a GZK flux to LIV, one can place *lower limits* on  $\alpha_\nu$ .<sup>19</sup> Figure 1 demonstrates the LIV modification<sup>14,19</sup> to a UHE- $\nu$  flux by a non-zero value of  $\alpha_\nu$ . Observation of one UHE- $\nu$  places *upper limits* on  $\alpha_\nu$  lower than those from atmospheric neutrinos, due to the energies and cosmological distances of GZK models. SME constraints will therefore be improved by enhanced ARA volume and the low-energy enhancement near  $10^{17} \text{ eV}$ .

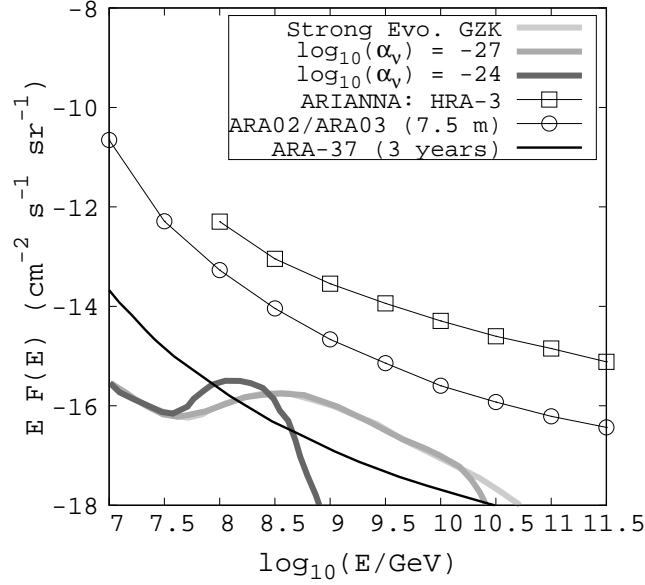


Fig. 1. The GZK-neutrino flux  $F(E)$  times the energy  $E_\nu$ , vs.  $E_\nu$ , are shown as the thick gray lines, with  $\alpha_\nu = 0$ ,  $\log_{10}(\alpha_\nu) = -27$ , and  $\log_{10}(\alpha_\nu) = -24$ . The current ARIANNA (HRA-3), ARA02/ARA03, and projected ARA-37 upper limits are shown as squares, circles, and the thin black line, respectively. The UHE- $\nu$  spectra are adapted from Gorham *et al.*<sup>19</sup>

#### 4. Future work

This *flavor blind* UHE- $\nu$  LIV scenario could be pushed further by at least two ideas. First, the charged leptons should cascade on the CMB/IR backgrounds, producing diffuse  $\gamma$ -rays.<sup>21</sup> Combining Fermi-LAT diffuse  $\gamma$ -ray observations and nonobservation of UHE- $\nu$  would lead to a restricted range for  $\alpha_\nu$ . Secondly, non-renormalizable, higher-dimensional SME operators also generate UHE- $\nu$  energy-loss, and the effect should increase dramatically with increasing energy, making UHE- $\nu$  an ideal messenger.<sup>22</sup> Recomputing the effective  $\alpha_\nu$  from these operators would produce the first limits on those SME coefficients. The effect should increase with energy, making UHE- $\nu$  analysis ideal.

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